Sludge Incineration and Precipitant Recovery

Volume III

Research Report No. 75

arch Program for the Abatement of Municipal Pollution
under Provisions of the Canada-Ontario Agreement
on Great Lakes Water Quality

CANADA-ONTARIO AGREEMENT

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These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Fisheries and Environment Canada, and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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SLUDGE INCINERATION AND PRECIPITANT RECOVERY

VOLUME III

Laboratory Scale Investigations

by

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RESEARCH PROGRAM FOR THE ABATEMENT OF MUNICIPAL POLLUTION UNDER THE PROVISIONS OF THE CANADA-ONTARIO AGREEMENT ON GREAT LAKES WATER QUALITY

Project No. 72-3-4

This document may be obtained from -

Training and Technology Transfer
Division (Water)
Environmental Protection Service
Environment Canada
OTTAWA, Ontario
KIA IC8

Ontario Ministry of the Environment
Pollution Control Branch
135 St. Clair Avenue West
TORONTO, Ontario
M4V IP5

Cat. No. En43-11/75

ISBN 0-662-01764-1

ABSTRACT

Samples of dewatered sludge were obtained from eight wastewater treatment plants in Ontario for laboratory scale experiments pertaining to sludge incineration. Selection of treatment plants was based on sludge type, treatment process, and the existence of sludge incineration facilities at three of these plants. Sludge types included raw primary, waste activated, and anaerobically digested mixed sludge. Four of the eight treatment plants were practicing phosphorus removal through chemical addition (alum, ferric chloride or lime).

Laboratory scale investigations consisted of determinations for total solids and volatile solids content, calorific values, tube furnace tests at temperatures over the range of 760°C (1 400°F) to 925°C (1 700°F), and thermogravimetric analyses over the temperature range from 200°C (390°F) to 925°C (1 700°F).

For the sludges investigated, total solids content ranged from 15% to 50% by weight while the volatile solids content was between 21% and 57% by weight of dry solids. Calorific values determined experimentally were compared with those calculated from three empirical equations. For seven of the eight sludges, the calculated values were within ±20% of the experimentally determined values. Tube furnace tests and thermogravimetric analyses showed that, for all samples, combustion of the organic matter was complete at 760°C (1 400°F) and that a constant weight of ash was produced for a particular sludge at combustion temperatures ranging from 760°C (1 400°F) to 925°C (1 700°F).

RÉSUMÉ

Huit usines d'épuration, en Ontario, ont fourni des échantillons de boues séchées en vue d'expériences d'incinération en laboratoire. Le type de boue et le procédé de traitement ont servi de critères dans le choix des usines. Trois d'entre elles ont également été sélectionnées parce qu'elles possédaient déjà l'équipement requis pour l'incinération. Les échantillons comprenaient des boues primaires brutes, des boues activées résiduaires et des boues mixtes digérées en milieu anaérobie. Quatre des huit usines effectuaient la déphosphatation par l'addition de produits chimiques tels que l'alun, le chlorure ferrique ou la chaux.

En laboratoire, on a évalué les matières totales, soit solides, soit volatiles, on a déterminé le pouvoir calorifique (PC) des boues et effectué des tests en four tubulaire à des températures variant de 760°C (1400°F) à 925°C (1700°F) ainsi que des analyses thermogravimétriques à des températures variant de 200°C (390°F) à 925°C (1700°F).

La teneur en matières solides totales variait de 15 à 50 p. 100 en poids tandis que la teneur en matières solides volatiles variait de 21 à 57 p. 100 en poids de matières sèches. Le pouvoir calorifique déterminé expérimentalement a été comparé aux résultats de trois équations empiriques. Le pouvoir calorifique de sept des huit boues, calculé selon ces équations, variait de ± 20 p. 100 des valeurs expérimentales. Les tests en four tubulaire et les analyses thermogravimétriques ont démontré que, pour tous les échantillons, la combustion des matières organiques était complète à 760°C (1400°F) et qu'on obtenait un poids constant de cendres à la suite de la combustion d'un type particulier de boue à des températures variant de 760°C (1400°F) à 925°C (1700°F).

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CONCLUSIONS

1. Sludge properties of special interest with respect to incineration are: moisture content, volatile solids content, amount and nature of fixed solids and calorific value. Reliable values for these sludge properties can be obtained in the laboratory through carefully conducted experiments.
2. The municipal wastewater sludges studied exhibited a broad range of calorific values depending upon the sludge type and pre-treatment process involved. In general, digested sludges have lower calorific values than raw primary or waste activated sludges, and chemical sludges have lower calorific values than do their non-chemical counterparts.
3. Addition of inorganic chemicals, such as lime and aluminum or iron salts, in the quantities normally used for phosphorus removal or sludge conditioning increases the concentration of inert material in the sludge mass and adversely affects the heat balance of the sludge combustion process.
4. The average calorific value for the eight sludges investigated was calculated to be 12 110 kJ/kg (5 210 BTU/lb) on a dry solids basis. Individual values spanned the range from 4 114 J/kg DS (1 770 BTU/lb DS), for a lime phosphorus removal sludge from a drying bed at the CFB Borden primary sewage treatment plant, to 16 570 kJ/kg (7 130 BTU/lb) of dry solids, for the heat treated sludge sample originating from the Mississauga Lakeview WPCP.
5. Calorific values calculated in this report using three different empirical equations generally compared favourably with each other. Except for the phosphorus removal lime sludge from CFB Borden, the estimated values fell within ±20% of the experimentally determined values.
6. Using data obtained in this study for chemical and non-chemical sludges, a linear mathematical relationship was established

between sludge volatile solids content and the experimentally observed calorific values. The equation derived for the eight sludges investigated is:

$$C_v(\text{kJ/kg DS}) = 291(\text{VS}) - 1\ 300$$

or: $$C_v(\text{BTU/lb DS}) = 128(\text{VS}) - 632$$

7. Tube furnace investigations and thermogravimetric analyses indicated very little, if any, volatilization of "fixed sludge solids" at combustion temperatures ranging from 760°C (1 400°F) to 925°C (1 700°F). Combustion of organic matter in the sludge is complete at these temperatures and constant ash production can be expected.
8. Tube furnace tests can provide useful information on the extent of volatile solids reduction as a function of temperature, the temperature range suitable for incineration of a particular sludge, and can indicate the temperature at which fusion of ash and clinker formation begins. This experimental technique is, however, severely limited in the information it can provide on important incinerator operating and design parameters such as: loading rate, residence time, excess air requirements, equipment size and auxiliary fuel requirements.

RECOMMENDATIONS

1. In investigations pertaining to sludge incineration, a characterization of the sludge, both as to its type and its treatment history, should be undertaken as these parameters influence the combustion properties of the sludge.
2. If reliable data for calorific values of wastewater sludges are desired, they should be obtained experimentally with a bomb calorimeter rather than by calculation from existing empirical equations.
3. Pilot and/or full scale studies should be conducted to extend the tube furnace investigations described herein and to provide

information on the optimum process parameters for incinerating sludges resulting from chemical wastewater treatment.

1 INTRODUCTION

Sewage sludge is a by-product of the physical, chemical and biological operations and processes employed in modern municipal wastewater treatment systems. Upgrading of municipal wastewater treatment facilities in Ontario and other parts of Canada is characterized by the generation of growing quantities of biological and chemical sludges which may be considerably more difficult to manage than traditional primary sludges (Proceedings of the Sludge Handling and Disposal Seminar, 1974; Schroeder and Cohen, 1976). Increasing population and the continuing trend towards urbanization can be expected to further burden municipal sludge handling, treatment and disposal facilities.

Effective sludge management is one of the most challenging aspects of wastewater treatment. Sludge is a liability rather than an asset to the wastewater treatment plant operator, because there is at present no means of disposing it at a profit. It has been estimated (Smith and Eilers, 1975) that treatment and disposal of sludges produced in municipal wastewater treatment plants can be responsible for as much as 60% of the total cost of operating and maintaining such facilities.

Various alternatives exist for the treatment and disposal of municipal wastewater sludge (Van Note et al, 1975; Vesilind, 1974; Farrell, 1974a). In the past, Canadian practice has generally been to select the least expensive option, often with little consideration to the environmental impact of the ultimate disposal process chosen (Black and Schmidtke, 1974). At present, viable alternatives for ultimate disposal of municipal sludge include agricultural land application, land reclamation, sanitary land filling and incineration.

Strictly speaking, incineration is ultimate disposal for the organic fraction of the sludge only, still leaving a residue (viz., ash) requiring final disposal. Attention has been focused in recent years on determining the feasibility of recycling or re-using incinerator ash for sludge conditioning (Smith et al, 1972), in structural fills and road sub-bases (Sutherland, 1968; Raymond and Smith, 1964), as a soil stabilizer, concrete additive, building block material and filler in asphalt mixes (Faber et al, 1970; Gray, 1970), as well as a construction material

(Gray and Penessis, 1972). Evaluation of various methods for removal and recovery of metals and other valuable constituents of sludge incinerator ash has been the subject of two previous reports in this series (Cambrian Processes Ltd., 1975; Oliver and Carey, 1976).

As land areas for drying beds, lagoons and landfills are becoming more difficult to locate and more costly to acquire, other methods of sludge disposal, particularly incineration, are gaining greater popularity. This situation is aggravated by mounting quantities of sludge requiring ultimate disposal as well as the encroachment of urban dwellings on many wastewater treatment plants which were previously remote. Sludge incineration is being incorporated into a growing number of water pollution control plants because it provides a proven and effective means of reducing wastewater sludge to an inert ash of relatively low bulk and weight in an environmentally acceptable manner. Typically, sludge volume is reduced by about 95%, while the ash that must be discarded accounts for approximately 10% by weight of the sludge cake fed to the incinerator. For many communities, with a significant industrial base, incineration will provide the only practical answer for disposal of their sewage sludge because of its content of heavy metals, toxic substances or other environmentally harmful constituents. In general, the choice between incineration or one of the other sludge disposal alternatives requires careful consideration of a number of factors including the quantity of sludge generated, its suitability for disposal on land, local climate (as it affects the seasonal nature of agricultural land application), availability of land, capital and operating expenses (including transportation and energy costs) of the various options available, as well as public opinion and environmental considerations.

In response to the recommendations contained in the 1969 International Joint Commission Report (Volume 1, Summary) and in anticipation of the Canada-US Agreement on Great Lakes Water Quality (1972), the governments of Canada and the Province of Ontario on August 13, 1971 signed an agreement to ensure that the water quality of the Great Lakes is restored and protected. One of the principal provisions of this

Canada-Ontario Agreement was to provide for the acceleration of the construction of municipal sewage treatment plants and to require the installation of phosphorus removal facilities at municipal and institutional wastewater treatment plants in the Great Lakes Basin. As a result of the selection of chemical precipitation processes for phosphorus removal, concern arose over the handling, treatment and disposal of the sludges produced. The use of chemicals in sewage treatment invariably increases the mass of sludge produced, generally increases the volume of sludge to be handled and disposed of, and alters its composition and chemical characteristics (Farrell, 1974b). Aluminum or iron salts and lime are the chemical agents primarily used for phosphorus removal.

2 OBJECTIVES

During 1972, the Wastewater Technology Centre (WTC) of the Environmental Protection Service (EPS) initiated an experimental program aimed at developing and demonstrating technology for sludge incineration and precipitant recovery applicable to municipal wastewater treatment sludges. The objective of this program was twofold: (1) to investigate the recovery of lime and iron from chemical phosphorus removal sludges for recycling these chemicals in the phosphorus removal process, and (2) to evaluate multiple-hearth incineration of alum, iron and lime sludges.

Sludge incineration, followed by recovery and recycling of phosphorus removal chemicals from the incinerator ash, holds considerable promise for reducing operating costs at wastewater treatment plants after phosphorus removal.

As part of this research and development program, one of the first activities was to conduct an extensive review of the literature on sludge incineration and precipitant recovery processes. The information was published as a coded bibliography report in this series (Plummer, 1976). Bench scale investigations to determine the feasibility of recovering and recycling iron from sludge incinerator ash are the subject of a separate publication (Fowlie and Stepko, 1978).

This report summarizes the findings of the laboratory scale investigations undertaken to supply basic information pertaining to the incineration characteristics of sludges from selected water pollution control plants in Ontario. The sludges studied were categorized as: alum, iron or lime sludge depending upon the chemical employed for phosphorus removal.

A subsequent report in this series will describe pilot scale studies designed to optimize multiple-hearth furnace operating parameters for an iron-rich sludge (Hamilton WPCP) and to establish scale-up relationships between pilot and full scale multiple-hearth sludge incinerators.

3 LITERATURE REVIEW

The first full scale sewage sludge incinerator in North America was installed in 1935 at Dearborn, Michigan (Groen, 1959). Today, there are in excess of 200 such operating installations in the US (Lewis, 1971). By comparison, in Canada there are at present only seven municipal wastewater sludge incinerators in operation, and three of these are located in Ontario. Hamilton, London and Metro Toronto each have sludge incinerators, and together incinerate approximately 40% of the sludge produced in the province (Black and Schmidtke, 1974; Antonic et al, 1978).

3.1 Sludge Characteristics

Sludge characteristics of primary interest with respect to incineration are moisture content and volatile solids content. Because of the large quantity of water associated with wastewater sludge, burning the liquid sludge separated at various stages in conventional wastewater treatment processes is considered impractical. The heat value of the combustible fraction of the solids in the liquid sludge mass is inadequate to evaporate the quantity of water which must be removed before combustion is self-sustaining. Table 1 summarizes typical values for total solids and volatile solids content of raw primary, waste activated, and digested sludge prior to dewatering (Metcalf and Eddy, Inc., 1972; US EPA, 1974).

TABLE 1. TYPICAL COMPOSITION OF RAW PRIMARY, WASTE ACTIVATED, AND DIGESTED SLUDGE

Solids Content \ Sludge Type	Raw Primary		Waste Activated		Digested	
	Range	Typical	Range	Typical	Range	Typical
Total Solids (TS) (%)	2 - 7	4	0.5 - 1.5	1	6 - 20	10
Volatile Solids (% of TS)	60 - 80	65	60 - 90	75	30 - 60	40

The moisture content of sludge is important in determining the quantity of auxiliary fuel required for incineration. The terms autogenous or auto-thermal sludge combustion refer to incineration under conditions such that no auxiliary fuel is required (except during start-up and shut-down of the incinerator). Autogenous incineration requires reduction of the sludge moisture content to about 65% (Burgess, 1968; Zajic, 1971; Loran, 1975). In addition to moisutre content, other factors which influence the potential of a particular sludge for self-sustaining combustion include: sludge type, volatile solids content, sludge treatment steps prior to incineration, and the thermal efficiency of the incineration unit (Warwick, 1974).

The calorific or gross heating value of a sludge is a function of its relative amount and elemental composition of the combustible matter contained in it and as such is related to its volatile solids content. Consequently, the carbon, hydrogen, oxygen, nitrogen and sulphur content is of interest when considering sludge disposal by incineration. Whereas C, H, O and N normally constitute the major components of the organic fraction of sludge, according to Harkness et al (1972), the total sulphur content of sludge solids is generally about 1% and rarely exceeds 2%, with about 60% as inorganic sulphur. Thus, the contribution of sulphur to the calorific value of wastewater sludge is usually negligible.

Table 2 summarizes the wide range of calorific values that have been reported for various types of municipal wastewater solids by different authors. The reported values range from 38 925 kJ/kg (16 750 BTU/lb) of dry solids, for grease and scum, to 9 760 kJ/kg (4 200 BTU/lb) of dry solids, for digested sludge, and reflect the diversity in chemical composition and volatile solids content of different types of wastewater residues. As a rule of thumb, the calorific value of sewage sludge is considered to be 23 000 kJ/kg (10 000 BTU/lb) of dry volatile solids. The actual fuel value of dewatered sludge cake at a total solids content of about 20% and a volatile solids content of approximately 70% would be 3 200 kJ/kg (1 400 BTU/lb) of wet sludge. Thus, sludge cake as fed to an incinerator has a relatively low fuel value and, in most instances,

TABLE 2. CALORIFIC VALUES REPORTED FOR VARIOUS TYPES OF MUNICIPAL WASTEWATER RESIDUES

Residue Type	Calorific Value, kJ/kg DS(BTU/lb DS)				
Grease and Scum	-	38 925 (16 750)	38 925 (16 750)	-	-
Raw Sewage Solids	-	23 900 (10 285)	23 900 (10 285)		
Raw Primary Sludge	18 985 (8 170)	22 080 (9 500)	18 175 (7 820)	16 270 (7 000)	19 520 (8 400)
Digested Sludge	15 990 (6 880)	12 295 (5 290)	12 295 (5 290)	12 780 (5 500)	9 760 (4 200)
Activated Sludge	19 985 (8 600)	-	15 200 (6 540)	16 270 (7 000)	19 520 (8 400)
Trickling Filter Sludge	13 990 (6 020)	-	-	-	-
REFERENCE	Reeve and Harkness, 1972	Owen 1957	Ford, 1970	McAteer, 1968	Loran, 1975

supplementary fuel (e.g., natural gas, digester gas, or fuel oil) is required for its combustion. By comparison, oil has a calorific value of approximately 44 000 kJ/kg (19 000 BTU/lb), coal approximately 32 500 kJ/kg (14 000 BTU/lb), and municipal solid waste about 11 500 kJ/kg (5 000 BTU/lb) (Vesilind, 1974; Chisamore, 1976).

The effects of anaerobic digestion and chemical precipitation in reducing the calorific value of sludge are shown in Table 3. In the past, the dry solids content of sludge was considered very important while insufficient attention was given to the influence of fixed solids content and chemical composition of the sludge, when considering its fuel value. As this table shows, chemical sludges are characterized by calorific values which are substantially less than those from raw primary sludges. Similarly, the anaerobic digestion process reduces the volatile solids content and increases the inert or non-combustible fraction of a sludge with a resultant decrease in its fuel value. One of the major objectives of sludge incineration is to achieve efficient combustion of

the volatile sludge solids (and hence maximum reduction in sludge volume) within the framework of existing design and/or operational constraints. Thus, maximum reduction of the volatile solids content presupposes incineration at, or above, a certain minimum temperature. Other requirements for efficient combustion of sludge include provision of a sufficient retention time and an adequate air supply. Virtually complete volume reduction of the volatile solids fraction of municipal wastewater sludges is generally believed to have occurred by the time the sludge temperature reaches 600°C (1 110°F) (Harkness et al, 1972). This temperature requirement is independent of the type of furnace (Burgess, 1968).

TABLE 3. EFFECTS OF SLUDGE TREATMENT PROCESSES ON CALORIFIC VALUE*

Sludge Type	Calorific Value	
	kJ/kg DS	BTU/lb DS
Raw primary	22 080	9 500
Chemically precipitated raw primary	16 290	7 010
Anaerobically digested raw primary	12 780	5 500

* U.S. EPA (1974).

Coupled with the need for efficient volume reduction during sludge incineration is a requirement for odour destruction. Sawyer and Kahn (1960), as a result of their investigations into temperature requirements for odour destruction in sludge incineration, concluded that the minimum temperature required varies somewhat with the character of the sludge processed and the method of concentration or conditioning. A reasonably safe temperature for odour destruction is 730°C (1 350°F) for most sludges, but 760°C (1 400°F) is required in some instances.

At the same time there exists a practical restriction on the maximum temperature for incinerating sludge. According to Burgess (1968) the temperature for sludge combustion must not exceed 1 040°C (1 900°F) or ash fusion with troublesome clinker formation occurs. Canadian experience (Shannon et al, 1974) has indicated that, for municipal

wastewater sludges containing inorganic chemicals - particularly iron and aluminum salts - problems with clinker formation may occur even below 1 000°C (1 830°F). Villiers (1973), in considering the impact of phosphorus removal sludges on conventional treatment and disposal processes, also presented some information regarding clinker formation during incineration of chemical phosphorus removal sludges.

3.2 Sludge Conditioning

Chemical conditioning of sludge is the most widely used pretreatment method for facilitating water removal during the dewatering process. Sludge, in effect, is a stable colloidal suspension and it is the function of a conditioner to destabilize this suspension. Organic polyelectrolytes as well as inorganic chemicals such as ferrous sulphate, ferric chloride and/or lime are employed. In recent years, polymer conditioning prior to dewatering has become so widespread that inorganic conditioners are generally used now only in situations where polymers have not yet been demonstrated to be economically effective, or on sludges for which polymers will not work. Estimates of the quantities of the common flocculating chemicals required for effective conditioning of a variety of wastewater sludges prior to vacuum filtration are given in Table 4 (US Environmental Protection Agency, 1974).

When inorganic chemicals are used in sludge conditioning, the weight of the sludge often increases by 10% or more and, because they contribute to the fixed solids content, the calorific value of the sludge is also reduced (Balakrishnan, 1970). Thus, the difference in calorific values between polymer conditioned sludges and those conditioned with inorganic flocculants should be considered if the sludge is to be incinerated. When organic polymers, rather than ferric chloride and lime, are used to condition sludge, the heat value of the resultant sludge cake can be increased by as much as 3 500 kJ/kg (1 500 BTU/lb) to 9 300 kJ/kg (4 000 BTU/lb) of dry solids. Furthermore, the quantity of ash from the furnace is likely to be reduced by 5% to 20% (Eckenfelder and Ford, 1970).

TABLE 4. ESTIMATED CHEMICAL CONDITIONING DOSAGE FOR VACUUM FILTRATION

Type of Sludge	CaO Dose kg/tonne (lb/ton)	$FeCl_3$ Dose kg/tonne (lb/ton)	Polymer Dose kg/tonne (lb/ton)
Primary Sludge	88 (176)	21 (42)	2.5 (5)
Limed Primary Sludge 106 kg CaO/tonne) (212 lb CaO/ton)	0	21 (42)	2.5 (5)
Digested Primary Sludge	120 (240)	38 (76)	10 (20)
Digested/Elutriated Primary Sludge	0	34 (68)	4.5 (9)
Raw (Primary + WAS)	100 (200)	26 (52)	9 (18)
Limed (Primary + WAS)	0	20 (40)	2.5 (5)
Digested (Primary + WAS)	186 (372)	55 (110)	18 (36)
Digested/Elutriated (Primary + WAS)	0	62.5 (125)	12 (24)

Incinerator ash has also been used as a conditioning agent to facilitate the removal of water from sludges (Harkness et al, 1972). Ratios of 1:1 sludge solids to ash for pressing, and 1:3 for sludge solids to ash for vacuum filtration were required. Sludge conditioned in this way tended to have a similar moisture content to sludge conditioned with chemicals, but a much lower calorific value. Increased consumption of auxiliary fuel during incineration would, therefore, be expected but increased fuel costs should be compared to cost reductions which may result in other unit operations and processes, as a result of ash utilization.

3.3 Sludge Dewatering

The primary objective of a dewatering operation is to reduce the sludge water content to a degree compatible with ultimate disposal of the resultant product. Factors affecting the dewaterability of wastewater sludge include (Burd, 1968):

(a) initial solids concentration;

(b) sludge age and temperature;

(c) sludge and filtrate viscosity;

(d) sludge compressibility;

(e) chemical composition; and,

(f) nature and pre-treatment of the sludge solids.

In general, the dewatering operation should capture practically all the solids in the sludge cake at minimum cost and the resultant cake should have optimal handling characteristics and moisture content for subsequent processing. Traditionally, drying beds are used to dewater sludges from wastewater treatment. Gale (1971) has pointed out some of the major limitations of this technique. Mechanical sludge dewatering devices, now in common use, include: rotary vacuum filters, centrifuges, plate and frame filter presses, and belt filter presses. Nevertheless, vacuum filters are still the most frequently encountered mechanical dewatering device and are applicable to all types of sewage sludges (Balakrishnan et al, 1970).

Dewatering of sludge is an extremely important pre-treatment step because the effectiveness of the dewatering process directly determines the moisture content of the incinerator feed and hence the amount of auxiliary fuel required for its combustion. Furthermore, to burn sludge in a multiple-hearth incinerator it must be dewatered to the consistency of a cake, i.e., >15% TS. Thus, material handling considerations also play a role in sludge dewatering. Gale (1972) has discussed, in some detail, heat balance considerations of sludge incineration, including the effect of the residual moisture content of sludge cake on the incineration process.

4 MATERIALS AND METHODS

4.1 Selection of Sludge Sources and Types

For this study, dewatered sludge samples were obtained from eight municipal wastewater treatment plants in Ontario. Criteria used in the selection process were:

(a) treatment plants with sludge incinerators (Toronto Main/Ashbridges Bay, London Greenway and Hamilton);
(b) sludge type (raw primary, raw mixed: primary plus waste activated, and digested mixed: primary plus waste activated); and,
(c) phosphorus removal chemical employed (lime, ferric chloride, alum).

The types of sludges investigated in this study and their points of origin are presented in Table 5. The sludge originating at the CFB Borden WPCP had been dewatered on a drying bed and that from the Windsor Little River WPCP had been centrifuged; the other sludges had been dewatered by vacuum filtration. Four of the eight water pollution control plants supplying sludge were using chemical phosphorus removal. Except for the sludge from CFB Borden and that from the Lakeview WPCP at Mississauga, which was conditioned by heat treatment, all sludges had been conditioned chemically with ferric chloride and/or lime, or polymer prior to the mechanical dewatering step. The Lakeview sludge was the only one of those selected which had not experienced chemical addition (neither for phosphorus removal nor for conditioning) and which could thus be regarded as a "non-chemical" type of municipal wastewater sludge.

4.2 Determination of Total and Volatile Solids Content

The total and volatile solids parameters were determined by procedures outlined in Standard Methods for the Examination of Water and Wastewater (1971).

TABLE 5. SLUDGE SOURCES AND TYPES

Sludge Source	Type of Sludge	Chemical(s) Added		Dewatering Method
		Phosphorus Removal[1]	Sludge Conditioning[2]	
CFB Borden	PR ND	Lime 150 - 250 mg/l	———	DB
Hamilton	PR + WAS AN D Iron-Rich	Before Implementation	Polymer 0.1 - 0.3%	VF
Toronto Main	PR + WAS AN D	Before Implementation	Polymer 0.5 - 0.7%	VF
Windsor West	PR ND	Alum 88 mg/l Polymer 0.3 mg/l	Ferric Chloride 0.4 - 1% Lime 10 - 15%	VF
Windsor Little River	PR + WAS ND	Alum 65 mg/l	Polymer 0.1 - 0.2%	C
London Greenway	PR + WAS ND	Before Implementation	Ferric Chloride 1.2 - 5.3% Lime 13.5 - 30%	VF
London Pottersburg	PR + WAS ND	Ferric Chloride 16 - 19 mg/l	Ferric Chloride 2.4 - 4.9% Lime 19 - 36%	VF
Mississauga Lakeview	70% PR (ND) + 30% (PR + WAS) (AN D)	Before Implementation	Thermal Conditioning by Wet Air Oxidation (LPO)	VF

[1] dosage expressed as weight of chemical added per unit volume of wastewater.
[2] dosage expressed as percent by weight of dry solids.

ND - no digestion.
AN D - anaerobic digestion.
PR - primary sludge.
WAS - waste activated sludge.
VF - vacuum filter.
C - centrifuge.
DB - drying bed.
LPO - low pressure oxidation.

4.3 Determination of Calorific Value

A plain (isothermal jacket) oxygen bomb calorimeter manufactured by the Parr Instrument Company (Instruction Manual No. 147, May, 1973) was employed to determine the gross heat of combustion for the sludges under investigation. Dried sludge samples weighing approximately one gram were used for these determinations. The energy equivalent of the bomb calorimeter was experimentally determined to be 2 612 cal/°C. Thermochemical corrections were applied to each experimental determination for the heats of formation of nitric acid and sulphuric acid, and the heat of combustion of the fuse wire. Sludge samples, in lump form were found to ignite more completely and to give more consistent results than samples which were ground.

4.4 Tube Furnace Investigations

Simulation of the sludge incineration process was carried out in a Lindberg Hevi-Duty tube furnace (Figure 1). Extra dry, clean air from a compressed air cylinder was passed through a 65 cm (25.6 in) long section of a Leco ceramic tube (2.5 cm or ∿1 in i.d.) of which 50 cm (∿20 in) was contained inside the tube furnace, the remainder projecting an equal distance from both ends of the furnace. The sludge sample, contained in a platinum sample boat, was initially positioned in the projecting portion of the tube down-stream of the tube furnace. In that position - corresponding to the drying zone of a multiple-hearth sludge incinerator - the sample is continuously swept by the air stream which has been pre-heated during its passage through the section of tube contained within the furnace. After a pre-determined period, the sample boat was advanced into the central portion of the tube which simulates the burning zone of a multiple-hearth incinerator. Simulation of the cooling zone of such an incinerator was achieved by moving the sample further upstream into the section of the ceramic tube ahead of the furnace.

The test procedure adopted was as follows. A weighed sample of sludge was detained in each of the three zones (drying, burning and cooling zone, respectively) for 20 minutes and was then placed in a

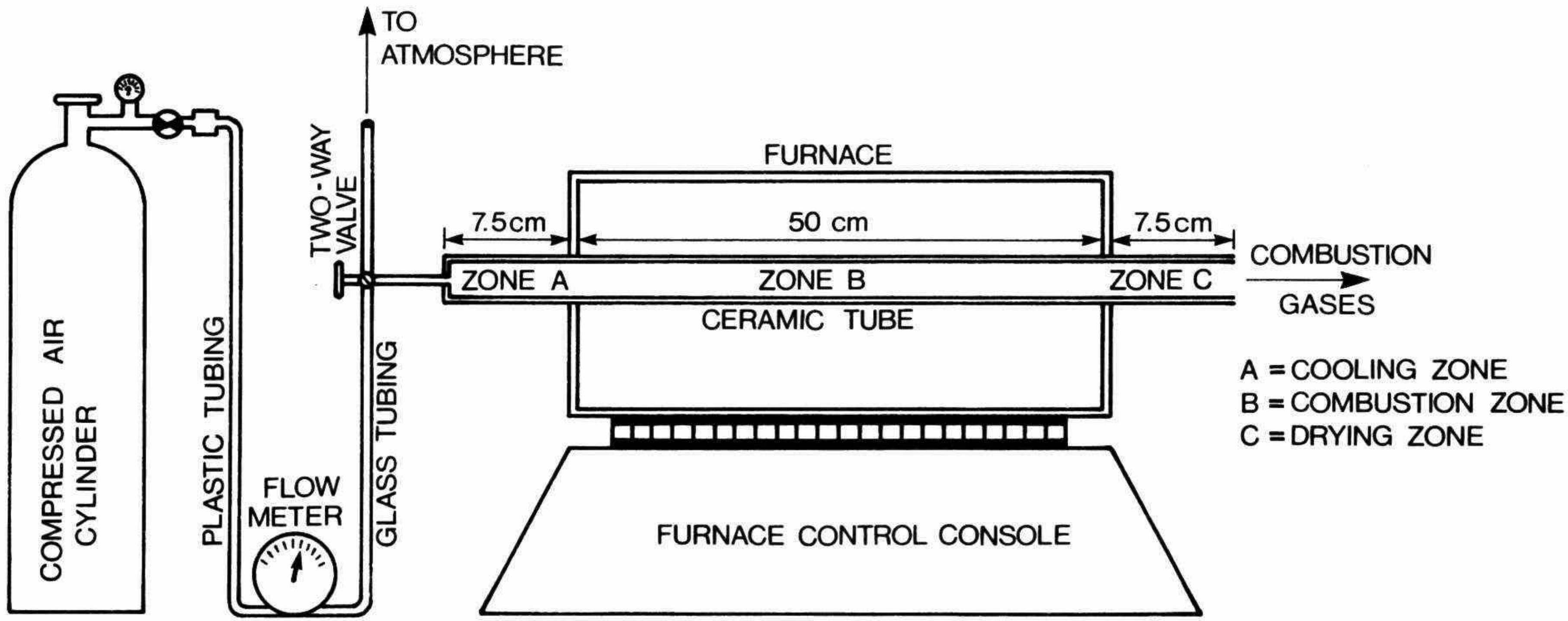

FIGURE 1 SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS FOR TUBE FURNACE INVESTIGATIONS

desiccator prior to determination of its residual weight. The flow rate of air was maintained at 1 000 cm^3/min during all experiments. Each sludge was investigated at tube furnace temperatures of 760°C (1 400°F), 815°C (1 500°F) and 925°C (1 700°F).

4.5 Thermogravimetric Analysis (TGA)

The experimental procedure for TGA was as follows. The sample of sludge cake was kept in a Cahn RG Electrobalance at 25°C (77°F) in a flow of dry air, until constant weight was reached. The heating program was then initiated, and the temperature of the sample was raised at approximately 10°C/min (18°F/min) to a maximum temperature of 925°C (1 700°F).

5 RESULTS AND DISCUSSION

5.1 Total and Volatile Solids Content of Sludge Samples

Total (dry) solids content and volatile solids content of the eight wastewater sludges studied are summarized in Table 6.

TABLE 6. TOTAL AND VOLATILE SOLIDS CONTENT OF SLUDGES INVESTIGATED

Sludge Source	Total Solids %		Volatile Solids % of TS	
	Range	Mean	Range	Mean
CFB Borden	32 - 50	42	19 - 24	21
Hamilton	15 - 20	18	42 - 50	46
Toronto Main	14 - 16	15	50 - 54	53
Windsor West	SV	22	39 - 45	42
Windsor Little River	SV	18	SV	52
London Greenway	SV	16	SV	51
London Pottersburg	SV	20	SV	48
Mississauga Lakeview	SV	50	SV	57

SV = single value.

The sludge from the Mississauga Lakeview plant exhibited the highest values for the total solids as well as for the volatile solids content. At this plant a low pressure wet air oxidation process is employed to condition the primary and waste activated sludge produced. Conditioning by heat treatment allows efficient operation of the rotary vacuum filters without addition of chemicals. Because this plant was not practicing phosphorus removal at the time the sludge was obtained, the sample contained neither conditioning nor phosphorus removal chemicals

of any kind. The sludge sample with the lowest dry solids content was obtained from the Toronto Main WPCP. This sample did exhibit a relatively high volatile solids content, however, even though the sludge had undergone stabilization by anaerobic digestion. The lime phosphorus removal sludge from one of the drying beds at the CFB Borden WPCP displayed a mean volatile solids content of only 21%. This relatively low value is attributed to the lime treatment and an advanced degree of mineralization due to prolonged storage in the drying bed.

The sample of raw primary sludge from the Windsor West WPCP was also characterized by a relatively low content of volatile solids. This plant serves the central core of the city of Windsor and receives residential, commercial and industrial waste emanating from a wide variety of chemical, metalworking and other heavy industry sources. The Little River WPCP, on the other hand, serves the eastern portion of Windsor and several of its suburbs - an area predominantly residential in nature (Anonymous, 1975). While both of these treatment plants used similar quantities of alum for phosphorus removal (see Table 5), Windsor West employed lime and ferric chloride for sludge conditioning, whereas the sludge at the Little River plant was conditioned with a polymer. These factors undoubtedly contributed to the higher total solids and lower volatile solids content determined for the sludge sample from the Windsor West WPCP. In the two London treatment plants from which dewatered sludge was obtained, the higher total solids content observed for the Pottersburg sample relative to that from Greenway probably resulted, at least in part, from the higher dosage of chemicals used at the Pottersburg WPCP (both for phosphorus removal and conditioning). As might be expected, the sludge from Pottersburg also had a lower volatile solids content when compared to that from the Greenway plant.

5.2 Calorific Values of Selected Wastewater Sludges

Calorific values, expressed on both a dry and a volatile solids basis, of dewatered sludge collected at the eight wastewater treatment plants are shown in Table 7.

TABLE 7. CALORIFIC VALUES OF SLUDGES FROM SELECTED WASTEWATER TREATMENT PLANTS IN ONTARIO

Sludge Source	Experimental Calorific Value			
	kJ/kg VS (BTU/lb DS)		kJ/kg VS (BTU/lb VS)	
	Range	Mean	Range	Mean
CFB Borden	3 790 - 4 455 (1 631 - 1 917)	4 120 (1 773)	23 686 - 27 844 (10 192 - 11 981)	25 752 (11 081)
Hamilton	11 738 - 13 240 (5 051 - 5 697)	12 340 (5 310)	24 681 - 29 382 (10 620 - 12 643)	26 826 (11 543)
Toronto Main	12 440 - 14 311 (5 353 - 6 158)	13 319 (5 731)	24 665 - 26 638 (10 613 - 11 462)	25 132 (10 814)
Windsor West	11 332 - 13 135 (4 876 - 5 652)	12 199 (5 249)	29 043 - 33 884 (12 497 - 14 580)	31 279 (13 459)
Windsor Little River	SV	14 839 (6 385)	SV	28 534 (12 278)
London Greenway	SV	11 566 (4 977)	SV	22 682 (9 760)
London Pottersburg	11 813 - 12 101 (5 083 - 5 207)	11 955 (5 144)	18 750 - 19 210 (8 068 - 8 266)	18 975 (8 165)
Mississauga Lakeview	SV	16 575 (7 132	SV	29 078 (12 512)

SV = single value.

The lowest calorific value was exhibited by the CFB Borden primary lime sludge. The surprisingly low calorific value for this sludge is a direct consequence of its treatment history. This statement is supported by the fact that the volatile solids content of this material averaged only 21% by weight of the dry sludge solids. Table 7 also shows that the highest calorific value was observed for the heat treated sludge from the Mississauga Lakeview WPCP. It contained approximately 50% by weight dry solids, 57% of which comprised volatile matter.

A higher calorific value (on a dry solids basis) was observed for mixed anaerobically digested sludge from Toronto Main than for the same type of sludge from the Hamilton plant. Possible reasons for this include differences in:

(a) relative amounts of primary and waste activated sludge which are combined;

(b) mode of operation of anaerobic digesters;

(c) sludge volatile solids content; and,

(d) nature of fixed sludge solids.

The effect of inorganic conditioning chemicals, specifically lime and ferric chloride, in depressing the calorific value of the resultant sludge is evident from a comparison of the results for Windsor West and Windsor Little River. At both treatment plants phosphorus removal was by addition of alum. However, at Windsor West the sludge was dewatered by vacuum filtration after addition of 10% to 15% lime and 0.4% to 1% ferric chloride, by weight. At the Windsor Little River plant the sludge was dewatered in a centrifuge after conditioning with 0.1% to 0.2% polymer.

Addition of alum for phosphorus removal results in the formation of aluminum hydroxide, $Al(OH)_3$. The addition of lime - either as CaO or as $Ca(OH)_2$ - and ferric chloride to sludge in the dewatering process results in the formation of calcium carbonate, $CaCO_3$, and ferric hydroxide, $Fe(OH)_3$, respectively. During combustion of the sludge these compounds undergo endothermic reactions according to the following thermochemical equations (Unterberg et al, 1971):

$$CaCO_3 + x\ (1\ 770\ \text{kJ/kg}\ CaCO_3) = x\ CaO + x\ CO_2 + (1-x)\ CaCO_3$$

$$Al(OH)_3 + y\ (887\ \text{kJ/kg}\ Al(OH)_3) = 1.5\ y\ H_2O + 0.5\ y\ Al_2O_3 + (1-y)\ Al(OH)_3$$

$$Fe(OH)_3 + z\ (523\ \text{kJ/kg}\ Fe(OH)_3) = 1.5\ z\ H_2O + 0.5\ z\ Fe_2O_3 + (1-z)\ Fe(OH)_3$$

where: x = fraction of calcium carbonate decomposed;
y = fraction of aluminum hydroxide decomposed; and
z = fraction of ferric hydroxide decomposed.

5.2.1 Correlation of calorific value and volatile solids content

The calorific values of the eight wastewater sludges investigated are plotted against their volatile solids content in Figure 2. A linear relationship between sludge volatile solids content and calorific value is clearly evident (correlation coefficient, $r = 0.93$). The line of best fit and the corresponding equation given in the figure were determined by the statistical method of least squares.

The calorific values for municipal wastewater sludges can thus be determined with a fair degree of confidence from a knowledge of their volatile solids content and through the use of an equation having the general form $y = ax + b$. Values for the coefficients a and b were found to be similar to those reported by Shannon et al (1974) for a different set of wastewater sludges generated at several sites in Ontario. These authors found that calorific values ranged from a low of 4 882 kJ/kg (2 100 BTU/lb) of dry solids for a primary lime sludge (lime dosage to raw wastewater = 250 mg/l as $Ca(OH)_2$) from the CFB Borden WPCP to a high of 18 590 kJ/kg (8 000 BTU/lb) of dry solids for a physical-chemical sludge consisting of activated carbon and primary alum sludge.

5.2.2 Comparison of experimental and calculated calorific values

A number of empirical relationships have been proposed for calculating the calorific value of wastewater sludges on the basis of their physical and/or chemical characteristics (Vesilind, 1974). One of the earliest methods of estimating calorific values - the Dulong formula - relies on the elemental composition of the sludge as derived from an ultimate analysis. The Dulong formula is:

$$C_v \text{ (BTU/lb DS)} = 145.4\,C + 620\,(H - \frac{O}{8}) + 41S \qquad (1)$$

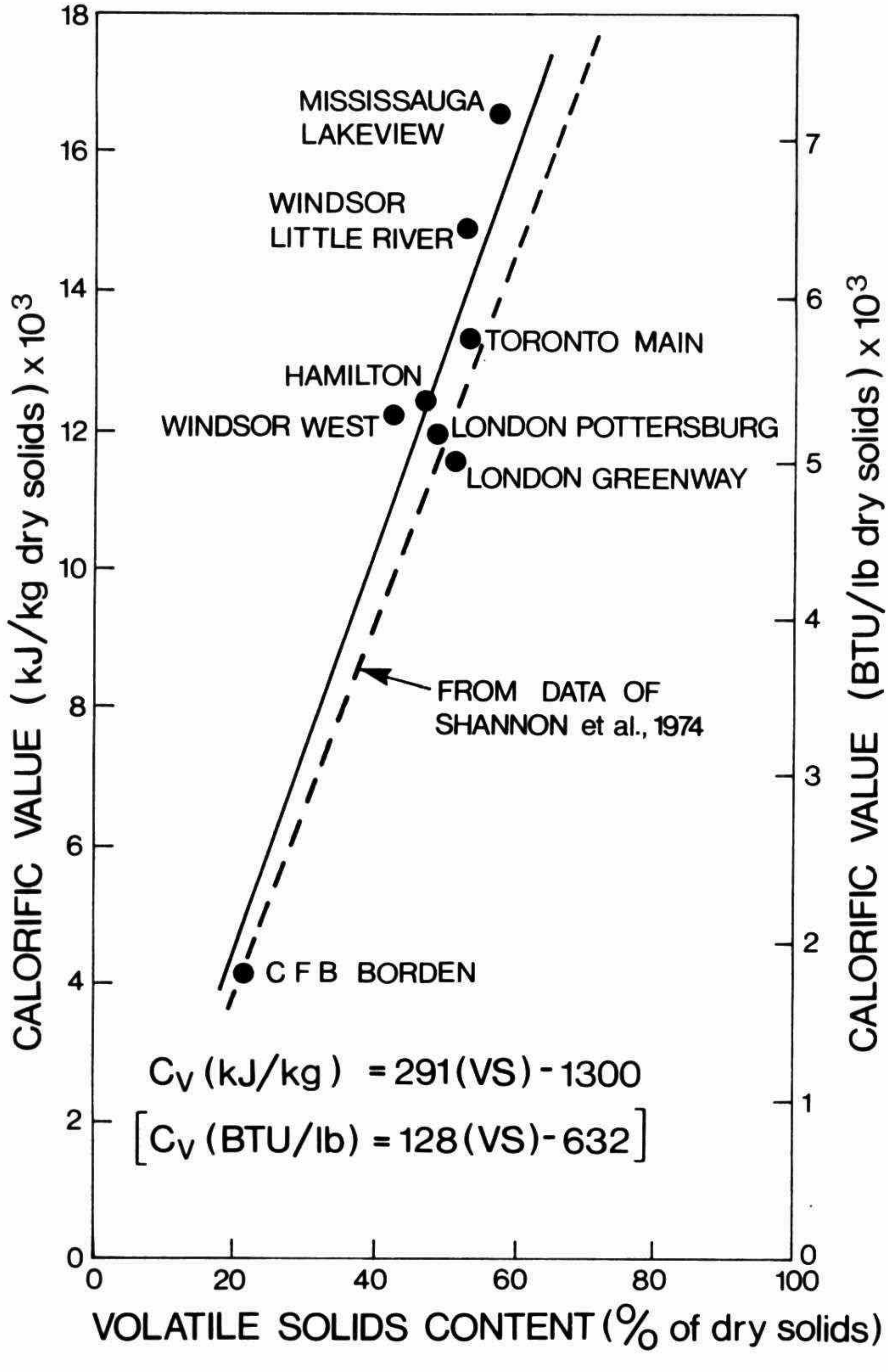

FIGURE 2 CALORIFIC VALUE - VOLATILE SOLIDS RELATIONSHIP FOR SELECTED SLUDGES

where C, H, O and S are the weight percentages in the sludge of carbon, hydrogen, oxygen and sulphur, respectively. The term $(H - \frac{O}{8})$ represents hydrogen that is combined with oxygen as moisture, as well as hydrogen and oxygen that are combined with the sludge in some other form. Owen (1957) has pointed out that the Dulong formula may give unsatisfactory answers for municipal wastewater sludges.

Rich (1963) has suggested another formula for estimating the calorific value of a sludge from a knowledge of its elemental composition:

$$C_v \text{ (kcal/kg DS)} = 127\,R + 400 \qquad (2)$$

where: $R = \dfrac{100(2.66\,C + 7.94\,H - O)}{398.9}$

and C, H and O are the percentages, on an ash-free weight basis, of carbon, hydrogen and oxygen, respectively. This formula does not take into account moisture or inert content of the sludge.

An empirical formula which is also applicable to chemically treated municipal sludges has been suggested by Fair et al (1968). These authors state that statistical correlation between experimentally observed calorific values and sludge volatile solids content is good and can be expressed as follows:

$$C_v \text{ (BTU/lb DS)} = A\left(\frac{100\ VS}{100 - D}\right) - B \times \left(\frac{100 - D}{100}\right) \qquad (3)$$

where: VS = volatile solids content as a percentage of total solids content;

D = dosage of chemical reagent used (for flocculation/precipitation or conditioning), expressed as percent by weight of sludge (D=0 for organic polymers);

A = an exmpirical coefficient: 107 for activated sludge and 131 for raw primary sludge; and

B = an empirical coefficient: 5 for activated sludge and 10 for raw primary sludge.

Still other relationships have been proposed by Niemitz (1965) and Kempa (1970). They are, respectively:

$$C_v \text{ (kcal/kg DS)} = 83.3\ X - 1089 \tag{4}$$

$$C_v \text{ (kcal/kg DS)} = 53.5\ Z + 365 \tag{5}$$

where: X = weight loss, expressed as a percentage of total solids content, upon ignition of sample (at 500°C); and

Z = weight loss, expressed as a percentage of total solids content, upon ignition of sample (temperature unspecified).

Using experimental data generated in this study, calorific values for the eight sludges investigated may be calculated by making appropriate substitutions in Equations (3), (4) and (5). In Table 8 the calorific values determined experimentally with a bomb calorimeter are compared with those calculated from these three empirical equations. Whereas Equations (4) and (5) take into account only the volatile solids content of the dry sludge solids, Equation (3) also takes into consideration the dosage of chemical reagent(s) added during sludge treatment operations or used for the purpose of phosphorus removal. It furthermore distinguishes between raw primary and activated sludge types.

Except for values calculated from Equations (4) and (5), for the primary lime sludge from CFB Borden, calorific values estimated by any one of the three equations fall within ±20% of the experimentally determined value. For the CFB Borden sludge, Equation (3) provides an excellent estimate of the calorific value. For both sludges originating from Windsor, all three empirical relationships significantly underestimate the calorific value. Again, with the exception of the CFB Borden sludge, Equations (4) and (5) consistently show the same trend in either over-estimating or underestimating the calorific value.

For each of the eight sludges studies, the reliability of the estimates produced by the three empirical equations were ranked by assigning a point of rating of three to the equation most closely approximating the experimental value, a point rating of two to that equation providing the next best estimate, and a point rating of one to the empirical equation providing the poorest approximation. From Table 9 Equation (5) may be seen to give the highest total point rating and Equation (3) the lowest total point rating. The differences in the

TABLE 8. COMPARISON OF EXPERIMENTAL AND CALCULATED CALORIFIC VALUES

Sludge Source	Experimentally Determined Calorific Value		Calorific Value Calculated By			% Difference Between Calculated and Experimental Values		
			BTU/lb DS	kcal/kg DS				
	kcal/kg DS	BTU/lb DS	Eq. (3)	Eq. (4)	Eq. (5)	Eq. (3)	Eq. (4)	Eq. (5)
CFB Borden	985	1 773	1 768 (D=25%)	660	1 489	- 0.3	- 33	+ 51
Hamilton	2 950	5 310	5 466 (D= 0%)	2 743	2 826	+ 9	- 7	- 4
Toronto Main	3 184	5 731	6 300 (D= 0%)	3 326	3 201	+ 10	+ 4	+ 0.5
Windsor West	2 916	5 249	4 540 (D=23%)	2 410	2 612	- 14	- 17	- 10
Windsor Little River	3 547	6 385	5 400 (D=10%)	3 243	3 147	- 15	- 9	- 11
London Greenway	2 765	4 977	5 407 (D=26%)	3 159	3 093	+ 9	+ 14	+ 12
London Pottersburg	2 858	5 144	5 111 (D=33%)	2 909	2 933	- 0.6	+ 2	+ 3
Mississauga Lakeview	3 962	7 132	5 890 (D= 0%)	3 659	3 415	- 17	- 8	- 14

Note: kcal/kg x 4.184 = kJ/kg.
D = dosage of chemical reagent used.
= 0 for organic polyelectrolytes.

total point ratings for the three equations are, however, probably too small to favour the use of Equation (5) to the point of excluding Equations (3) and (4) from consideration. Because the results of all three equations significantly differ from the experimentally determined values in several instances, the empirical equations should not be used in circumstances where an accurate value for the calorific value of a sludge is required. In such circumstances careful bomb calorimetric determinations should be performed.

TABLE 9. RELIABILITY RANKING OF THREE EMPIRICAL EQUATIONS FOR ESTIMATING SLUDGE CALORIFIC VALUE

Sludge Source	Point Rating		
	Equation (3)	Equation (4)	Equation (5)
CFB Borden	3	2	1
Hamilton	1	2	3
Toronto Main	1	2	3
Windsor West	2	1	3
Windsor Little River	1	3	2
London Greenway	3	1	2
London Pottersburg	3	2	1
Mississauga Lakeview	1	3	2
TOTAL POINT RATING	15	16	17

5.3 Tube Furnace Investigations

As part of these laboratory scale studies, the combustion and weight loss characteristics of seven sludge samples were investigated in a tube furnace between 760°C (1 400°F) and 925°C (1 700°F). The experimental procedure followed was described previously (Section 4.4). Selection of the lower limit for this temperature range was based on the requirement for odour destruction, while the upper temperature limit in the tube furnace was determined by the need to avoid fusion of the ash and clinker formation.

The experimental results for changes in sample weight observed for sludges from CFB Borden, Hamilton, Windsor West, Windsor Little River, London Greenway and London Pottersburg at tube furnace temperatures of 760°C (1 400°F) to 925°C (1 700°F) are shown in Figure 3. Sample weight remained constant over this range of temperatures for the sludges from Windsor Little River, London Pottersburg and Hamilton. A slight loss in weight under the same experimental conditions occurred for the sludges from Windsor West, London Greenway and CFB Borden. This apparent loss in sample weight was less than 5% in all three cases, being of the same order of magnitude as the experimental error. Should the weight loss observed constitute a real phenomenon, it would mean that one or more constituents of the sludge exhibit volatility over this temperature range. There does not appear to be any direct correlation between sludge type or treatment history and the observations on sample weight as a function of tube furnace temperature for these sludges. The investigations showed that combustion of the organic matter in the wastewater sludges was complete at 760°C (1 400°F) and that little, if any, further reduction in weight occurred between 760°C (1 400°F) and 925°C (1 700°F).

Figure 4 displays the results of tube furnace tests conducted on five samples of vacuum filter cake collected at the Toronto Main (Ashbridges Bay) WPCP on May 1 to 3 and 5 to 6, 1975, and designated ABB-1, ABB-2, ABB-3, ABB-5 and ABB-6, respectively. For sample ABB-3 there was no change in weight over the temperature range from 760°C (1 400°F) to 925°C (1 700°F). The apparent temperature dependence of the weight loss for the other sludge samples was of the same order of magnitude as the experimental error (±5%) and thus could not definitely be attributed to volatilization of certain sludge constituents in this temperature range.

Because of an uncertainty regarding possible weight losses in this temperature range, stemming from results obtained during the tube furnace work on some of these sludge samples (particularly ABB-3 and ABB-6) portions of these two samples were submitted for thermogravimetric analysis (TGA).

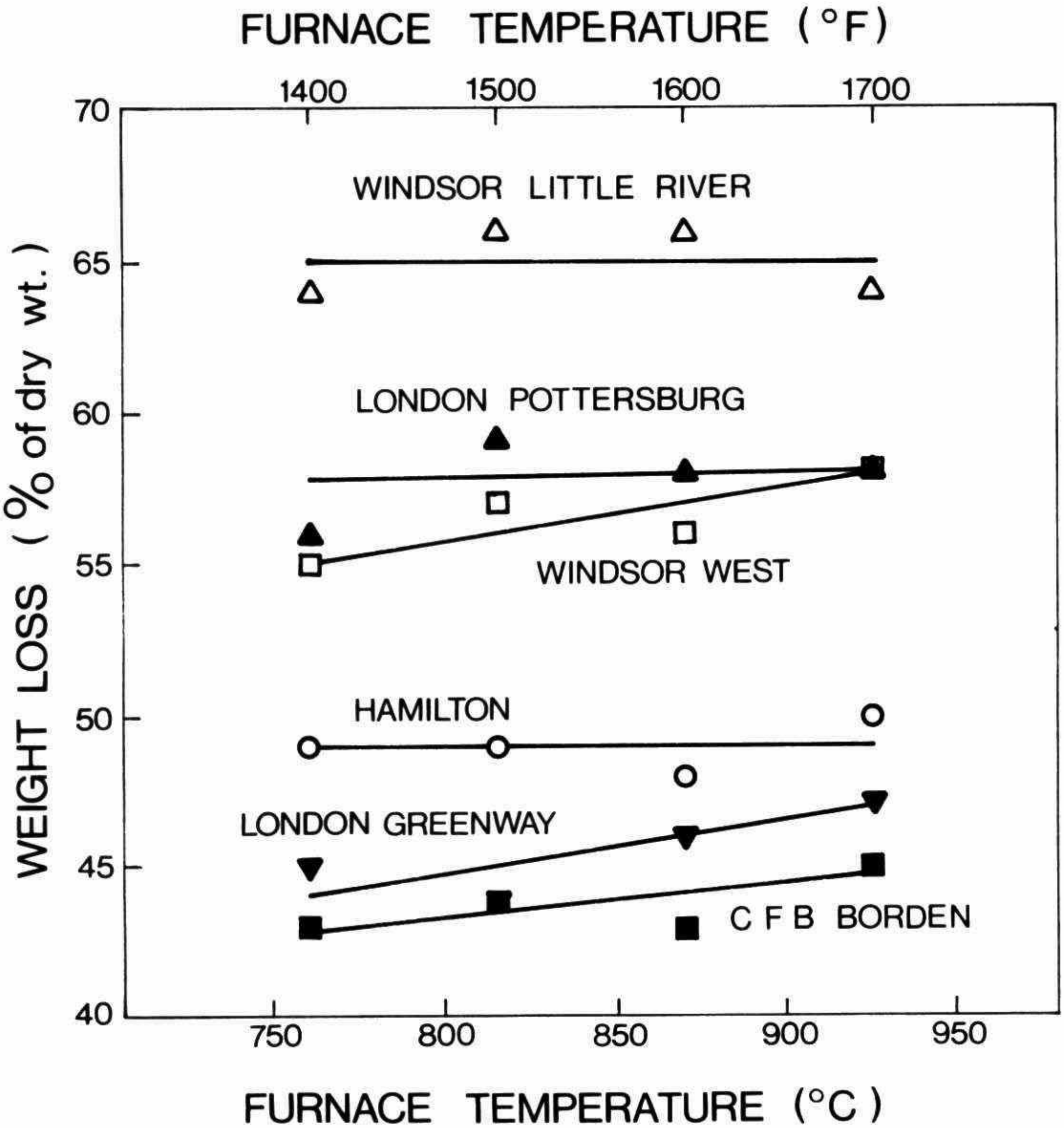

FIGURE 3 SLUDGE WEIGHT LOSS AT VARIOUS TUBE FURNACE TEMPERATURES

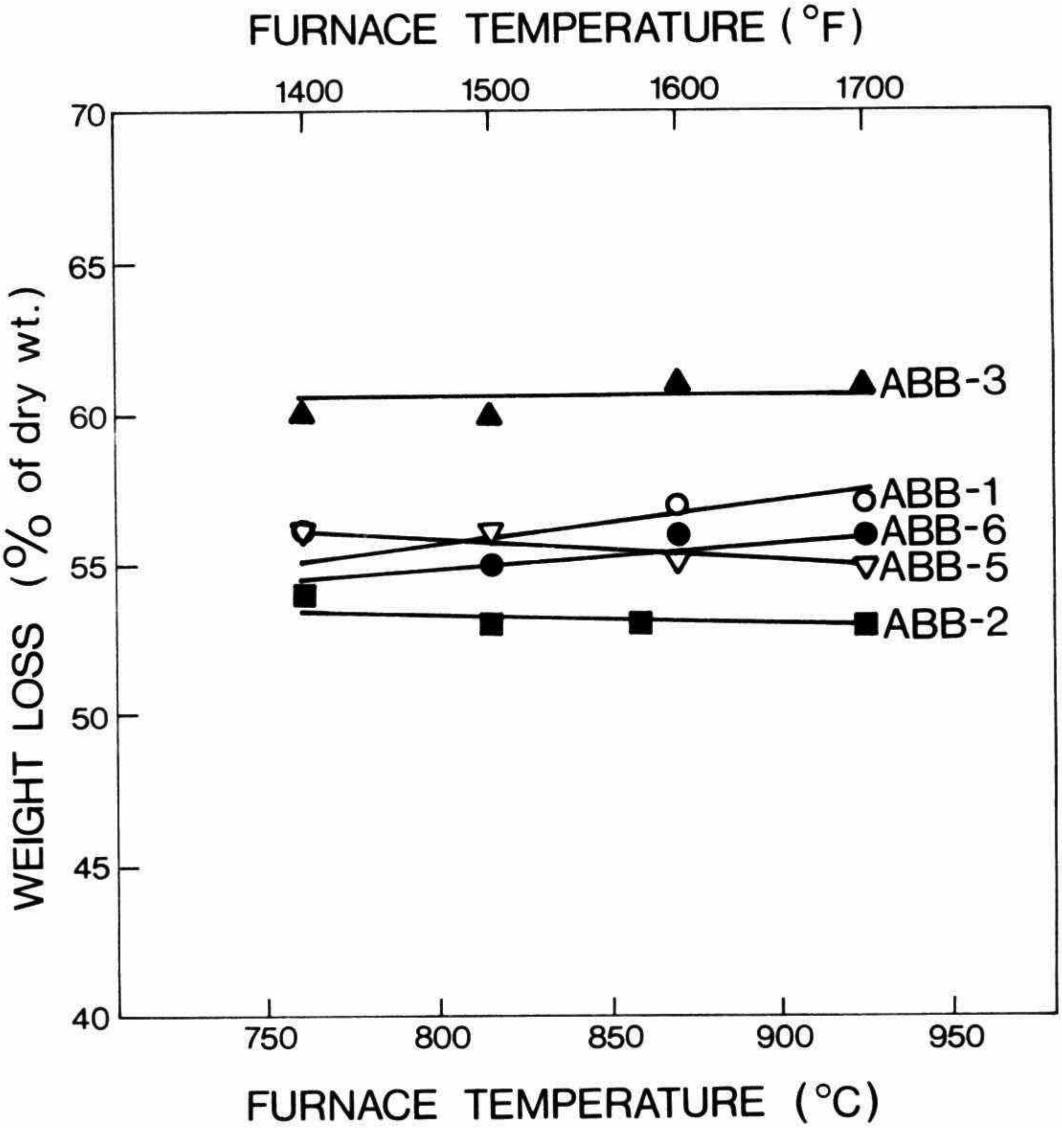

FIGURE 4 SLUDGE WEIGHT LOSS AT VARIOUS TUBE FURNACE TEMPERATURES (TORONTO MAIN WPCP SAMPLES)

The TGA results are shown in Figure 5. During these analyses, weight loss at temperatures between 20°C (68°F) and 200°C (390°F) (corresponding primarily to evaporation of moisture) was found to be not reproducible in duplicate experiments performed on each of the two sludge samples. However, weight loss in the temperature range from 200°C (390°F) to 925°C (1 700°F) was found to be well reproducible for each sample. For both samples, about 99% of the total weight loss had occurred by the time the temperature reached 760°C (1 400°F). Thus, in the temperature range of 760°C (1 400°F) to 925°C (1 700°F) there was no further significant change in the weight of the samples analyzed by TGA. Similar results would be expected for the other sludges selected for this study. Thermogravimetric analyses thus clarified and substantiated the results from our previous tube furnace investigations.

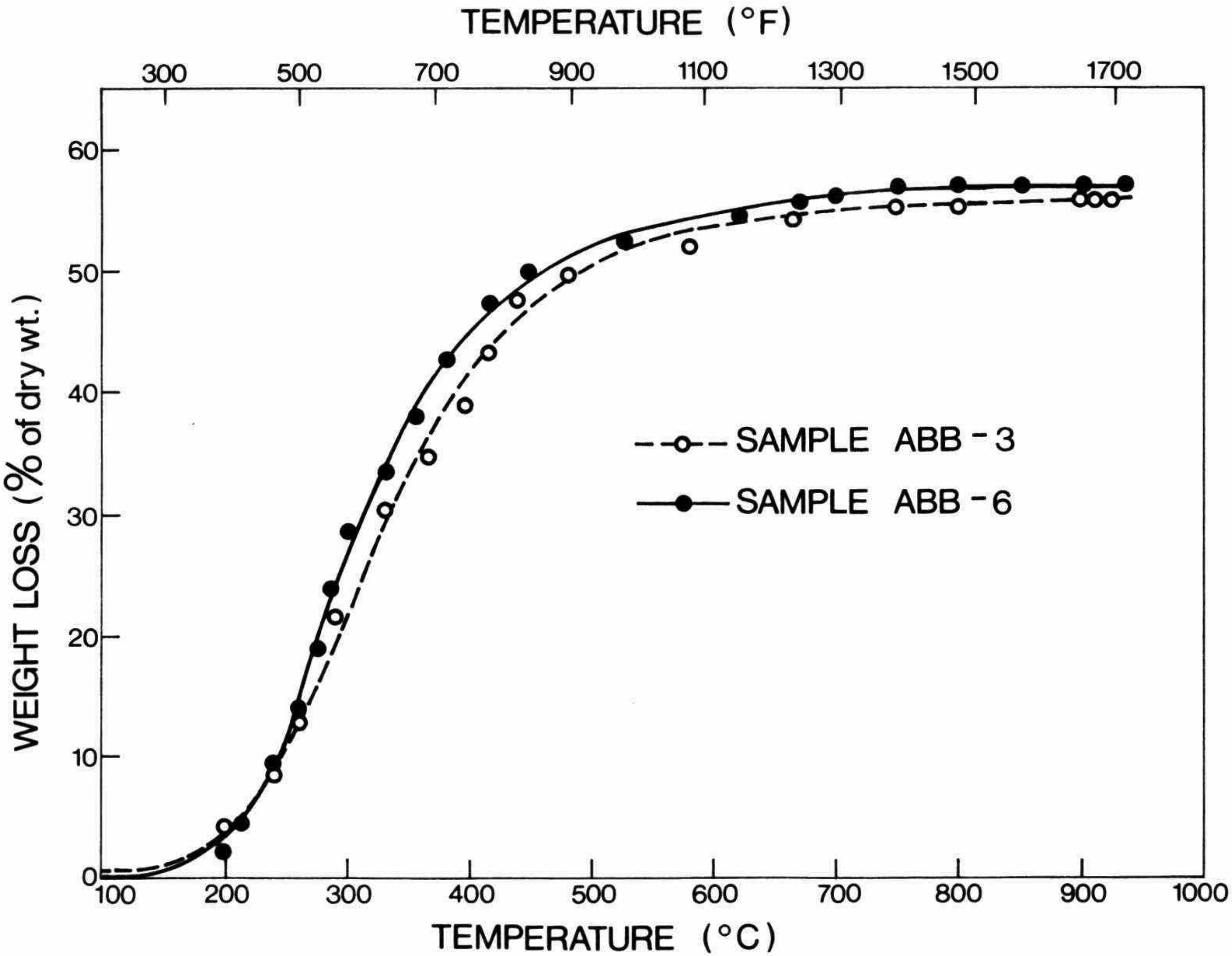

FIGURE 5 RESULTS OF THERMOGRAVIMETRIC ANALYSIS OF DEWATERED SLUDGE FROM TORONTO MAIN WPCP

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ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial assistance provided by the Governments of Canada and the Province of Ontario under the research program of the Canada-Ontario Agreement on Great Lakes Water Quality.

Participation in, and contributions to, this project by the following persons from the Wastewater Technology Centre are gratefully acknowledged:

Dr. E.E. Shannon	Mr. W.E. Stepko
Mr. D. Plummer	Dr. R. Rosehart
Mr. B. Cross	Mr. B. Prested

Special thanks are due to Mr. P. Crescuolo for data reduction and data analysis. The authors would also like to express their gratitude to the management and staff at the eight wastewater treatment plants from which sludge samples were obtained for this study.